CHAPTER 5

CONCEPTS OF ALTERNATING CURRENT

INTRODUCTION

Thus far this text has dealt with direct current (DC); that is, current that does not change direction. However, a coil rotating in a magnetic field actually generates a current that regularly changes direction. This current is called alternating current (AC).

AC AND DC

Alternating current is current that changes constantly in amplitude and which reverses direction at regular intervals. Direct current flows only in one direction. The amplitude of current is determinedly the number of electrons flowing past a point in a circuit in one second. If, for example, a coulomb of electrons moves past a point in a wire in one second and all of the electrons are moving in the same direction, the amplitude of DC in the wire is 1 amp. Similarly, if half a coulomb of electrons moves in one direction past a point in the wire in half a second, then reverses direction and moves past the same point in the opposite direction during the next half-second, a total of 1 coulomb of electrons passes the same point in the wire. The amplitude of the AC is 1 ampere. Figure 5-1 shows this comparison of DC and AC. Notice that one white arrow plus one striped arrow comprises 1 coulomb.

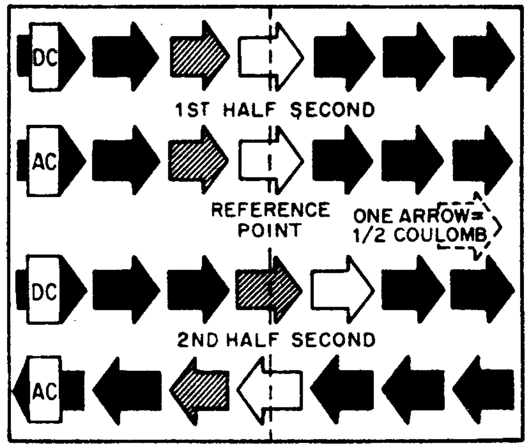


FIGURE 5-1. Comparing DC and AC Current Flow in a Wire.

DISADVANTAGES OF DC COMPARED TO AC

When commercial use of electricity became widespread in the United States, certain disadvantages in using DC became apparent. If a commercial DC system is used, the voltage must be generated at the level (amplitude or value) required by the load. To properly light a 240-volt lamp, for example, the DC generator must deliver 240 volts. If a 120-volt lamp is to be supplied power from a 240-volt generator, a resistor or another 120-volt lamp must be placed in series with the 120-volt lamp to drop the extra 120 volts. When the resistor is used to reduce the voltage, an amount of power equal to that consumed by the lamp is wasted.

Another disadvantage of the DC system becomes evident when the direct current (I) from the generating station must be transmitted a long distance over wires to the consumer. When this happens, a large amount of power is lost due to the resistance (R) of the wire. The power lost equals I^2R. However, this loss can be greatly reduced if the power transmitted over the lines is at a very high voltage level and a low current level. This is not a practical solution in the DC system since the load would then have to be operated at a dangerously high voltage. Because of the disadvantages related to transmitting and using DC, practically all modern commercial electric power companies generate and distribute AC.

Unlike direct voltages, alternating voltages can be stepped up or down in amplitude by a device called a transformer. Use of the transformer permits efficient transmission of electrical power over long distance lines. At the electrical power station, the transformer output is at high voltage and low current levels. At the consumer end of the transmission lines, the voltage is stepped down by a transformer to the value required by the load. Due to its inherent advantages and versatility, AC has replaced DC in all but a few commercial power and vessel applications.

ELECTROMAGNETISM

The sine wave is used to illustrate the change in current direction of the AC system. Although there are several ways of producing this current, the method based on the principles of electromagnetic induction is by far the easiest and most common method in use.

Chapter 2 discussed the fundamental theories concerning simple magnets and magnetism, but it only briefly mentioned how magnetism can be used to produce electricity. This chapter presents a more in-depth study of magnetism. The main points are how magnetism is affected by an electric current and, conversely, how electricity is affected by magnetism. This general subject area is called electromagnetism. The following relationships between magnetism and electricity must be understood to become proficient in the electrical field:

- An electric current always produces some form of magnetism.
- The most commonly used means for producing or using electricity involves magnetism.
- The peculiar behavior of electricity under certain conditions is caused by magnetic influences.

MAGNETIC FIELDS

In 1819, Hans Christian Oersted, a Danish physicist, found that a definite relationship exists between magnetism and electricity. He discovered that an electric current is always accompanied by certain magnetic effects and that these effects obey certain laws.

MAGNETIC FIELD AROUND A CURRENT-CARRYING CONDUCTOR

If a compass is placed near a current-carrying conductor, the compass needle will align itself at right angles to the conductor. This indicates the presence of a magnetic force. The presence of this force can be demonstrated by using the arrangement in Figure 5-2. In views A and B, current flows in a vertical conductor through a horizontal piece of cardboard. The direction of the magnetic field produced by the current can be determined by placing a compass at various points on the cardboard and noting the compass needle deflection. The direction of the magnetic force is assumed to be the direction in which the north pole of the compass points.

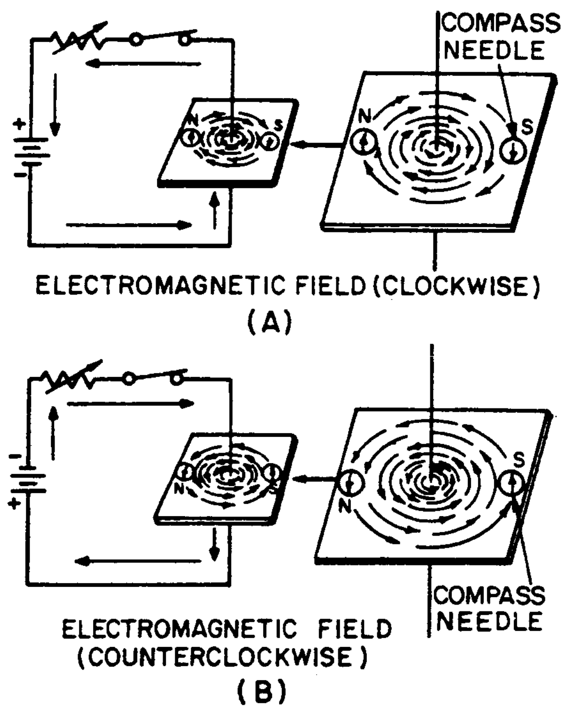


FIGURE 5-2. Magnetic Field Around a Current-Carrying Conductor.

In view A, the needle deflections show that a magnetic field exists in a circular form around a conductor. When the current flows upward (view A), the direction of the field is clockwise as viewed from the top. However, if the polarity of the battery is reversed so that the current flows downward (view B), the direction of the field is counterclockwise.

The relation between the direction of the magnetic lines of force around a conductor and the direction of the current in the conductor may be determined by means of the left-hand rule for a conductor. If you visualize the conductor in the left hand with your thumb extended in the direction of the electron flow (current: - to +), your finger will point in the direction of the magnetic lines of force. Now apply this rule to Figure 5-2. Note that your fingers point in the direction that the north pole of the compass points when it is placed in the magnetic field surrounding the wire.

An arrow is generally used in electrical diagrams to denote the direction of current in a length of wire (Figure 5-3 view A). Where across section of wire is shown, an end view of the arrow is used. View B shows a cross-sectional view of a conductor carrying current toward the observer. The direction of current is indicated by a dot, representing the head of an arrow. View C shows a conductor carrying current away from the observer. The direction of current is indicated by a cross, representing the tail of the arrow. The magnetic field around the current-carrying conductor is perpendicular to the conductor, and the magnetic lines of force are equal along all parts of the conductor.

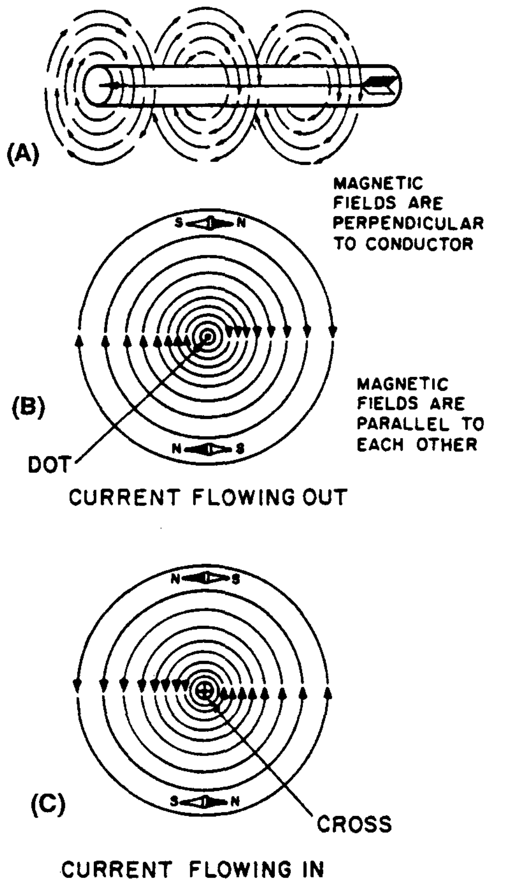


FIGURE 5-3. Magnetic Field Around a Current-Carrying Conductor, Detailed View.

When two adjacent parallel conductors are carrying current in the same direction, the magnetic lines of force combine and increase the strength of the magnetic field around the conductors (Figure 5-4 view A). View B shows two parallel conductors carrying currents in opposite directions. The field around one conductor is opposite in direction to the field around the other conductor. The resulting lines of force oppose each other in the space between the wires, thus deforming the field around each conductor. This means that if two parallel and adjacent conductors are carrying currents in the same direction, the fields about the two conductors aid each other. Conversely, if the two conductors are carrying currents in opposite directions, the fields about the conductors repel each other.

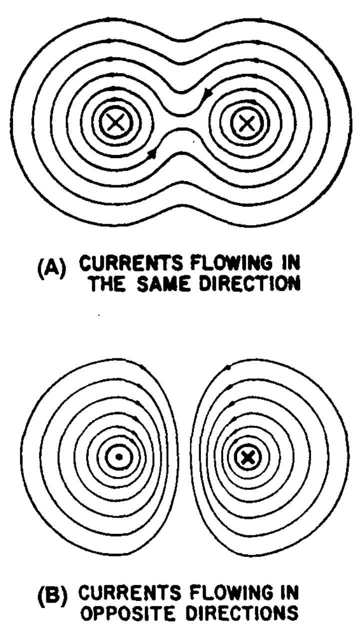


FIGURE 5-4. Magnetic Field Around Two Parallel Conductors.

MAGNETIC FIELD OF A COIL

Figure 5-3 view A shows that the magnetic field around a current-carrying wire exists at all points along the wire. Figure 5-5 shows that when a straight wire is wound around a core, it forms a coil, and the magnetic field about the core assumes a different shape. Figure 5-5 view A is actually a partial cutaway view showing the construction of a simple coil. View B shows a cross-sectional view of the same coil. The two ends of the coil are identified as X and Y.

When current is passed through the coil, the magnetic field about each turn of wire links with the fields of the adjacent turns (Figure 5-4). The combined influence of all the turns produces a two-pole field similar to that of a simple bar magnet. One end of the coil is a north pole and the other a south pole.

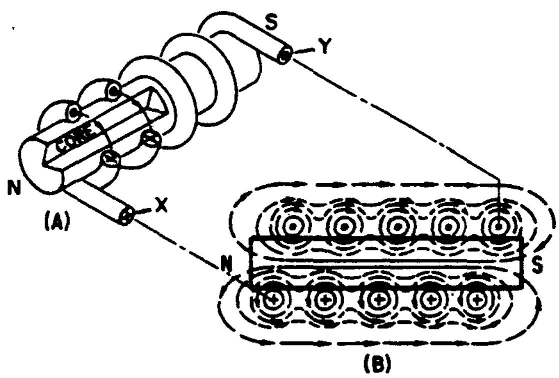


FIGURE 5-5. Magnetic Field Produced By a Current-Carrying Coil.

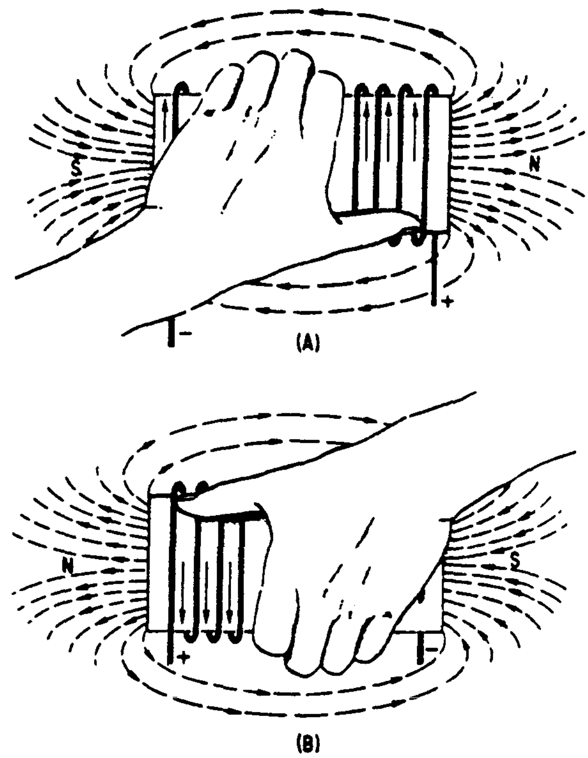


FIGURE 5-6. Left-Hand Rule for Coils.

Polarity of an Electromagnetic Coil

The direction of the magnetic field around a straight wire depends on the direction of current in that wire, as shown in Figure 5-2. Thus, a reversal of current in a wire causes a reversal in the direction of the magnetic field that is produced. It follows that a reversal of the current in a coil also causes a reversal of the two-pole magnetic field about the coil.

When the direction of the current in a coil is known, the magnetic polarity of the coil can be determined by using the left-hand rule for coils. This rule, illustrated in Figure 5-6, is stated as follows:

> Grasp the coil in your left hand, with your fingers wrapped around in the direction of the current. Your thumb will then point toward the north pole of the coil.

Strength of an Electromagnetic Field

The strength or intensity of a coil's magnetic field depends on a number of factors. The main factors are as follows:

- The number of turns of wire in the coil.
- The amount of current flowing in the conductor.
- The ratio of the coil length to the coil width.
- The type of material in the core.

Losses in an Electromagnetic Field.

When current flows in a conductor, the atoms line up in a definite direction, producing a magnetic field. When the direction of current changes, the direction of the atom's alignment also changes, causing the magnetic field to change direction. To reverse all the atoms requires that power be expended, and this power is lost. This loss of power (in the form of heat) is called hysteresis loss. Hysteresis loss is common to all AC equipment. However, it causes few problems except in motors, generators, and transformers.

BASIC AC GENERATION

A current-carrying conductor produces a magnetic field around itself. Chapter 2 discussed how a changing magnetic field produces an EMF in a conductor. If a conductor is placed in a magnetic field and either the field or the conductor moves in such a manner that lines of force are interrupted, an EMF is induced in the conductor. This effect is called electromagnetic induction.

CYCLE

Figure 5-7 shows a suspended loop of wire (conductor) being rotated (moved) in a clockwise direction through the magnetic field between the poles of a permanent magnet. For easy explanation, the loop has been divided into a dark half and a light half. In Figure 5-7 view A, the dark half is moving along (parallel to) the lines of force. As a result, it is cutting no lines of force. The same is true of the light half, which is moving in the opposite direction. Since the conductors are cutting no lines of force, no EMF is induced.

As the loop rotates toward the position in Figure 5-7 view B, it cuts more and more lines of force per second (inducing an ever-increasing voltage) because it is cutting more directly across the field (lines of force). At view B, the conductor has completed one-quarter of a complete revolution (90 degrees) of a complete circle. Because the conductor is now cutting directly across the field, the voltage induced in the conductor is maximum. If the induced voltages at various points during the rotation from views A to B are plotted on a graph (and the points connected), a curve appears as shown in Figure 5-8.

As the loop continues to be rotated toward the position in Figure 5-7 view C, it cuts fewer and fewer lines of force. The induced voltage decreases from its peak value. Eventually, the loop is again moving in a plane parallel to the magnetic field, and no EMF is induced in the conductor.

The loop has now been rotated through half a circle (an alternation or 180 degrees). If the preceding quarter-cycle is plotted, it appears as shown in Figure 5-8.

When the same procedure is applied to the second half of the rotation (180 degrees through 360 degrees), the curve appears below the horizontal time line. The only difference is in the polarity of the induced voltage. Where previously the polarity was positive, it is now negative.

The sine curve shows the induced voltage at each instant of time during the rotation of the loop. This curve contains 360 degrees, or two alternations. Two alternations represent one complete cycle of rotation.

Assuming a closed circuit is provided across the ends of the conductor loop, the direction of current in the loop can be determined by using the left-hand rule for generators (Figure 5-9). The left-hand rule is applied as follows:

- First, place your left hand near the illustration with the fingers as shown.
- Your thumb will point in the direction of rotation (relative movement of the wire to the magnetic field). The forefinger will point in the direction of the magnetic flux (north to south). The middle finger (pointing out of the paper) will point in the direction of current flow.

When applying the left-hand rule to the dark half of the loop in Figure 5-8 view B, the current flows in the direction indicated by the heavy arrow. Similarly, when applying the left-hand rule on the light half of the loop, the current flows in the opposite direction. The two induced voltages in the loop add together to form one total EMF. This EMF causes the current in the loop.

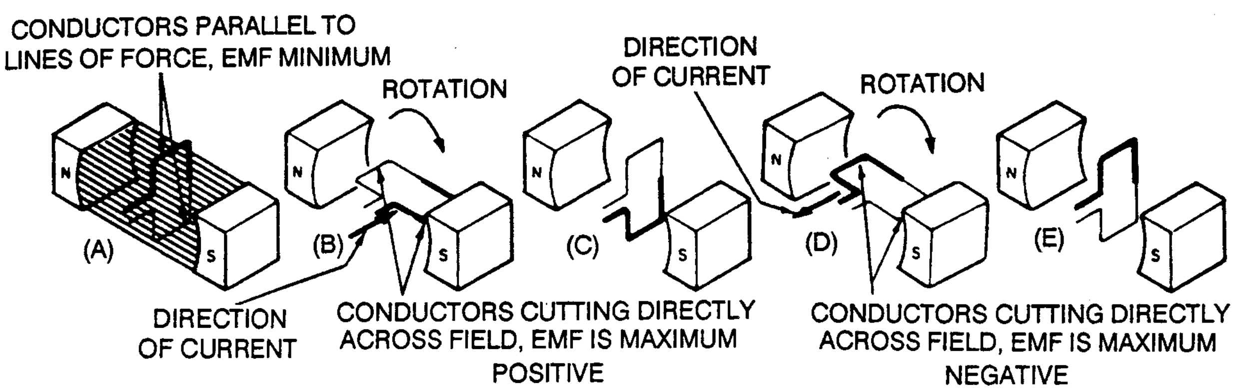


FIGURE 5-7. Simple Alternating Current Generator.

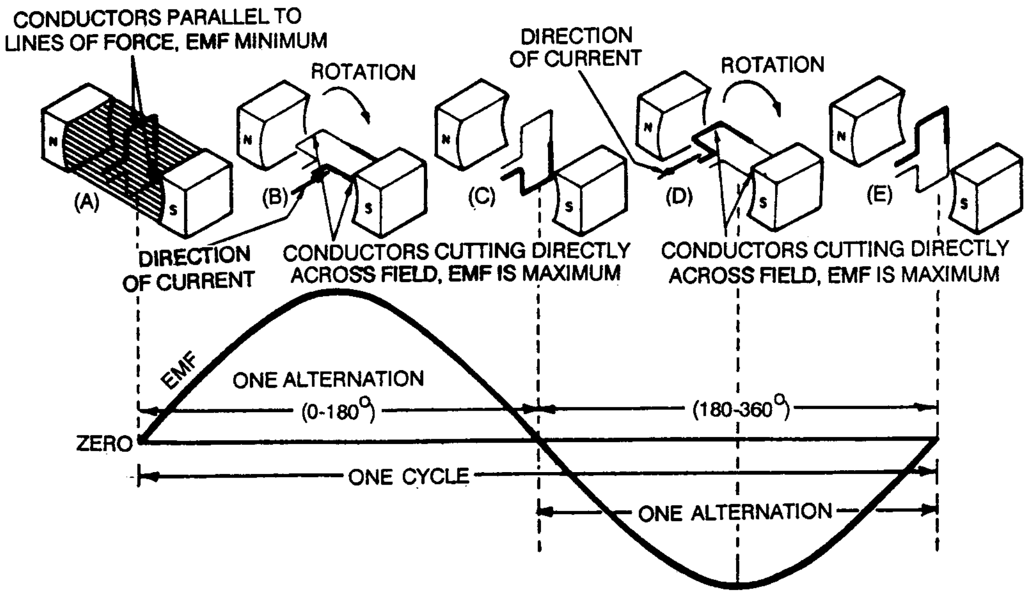
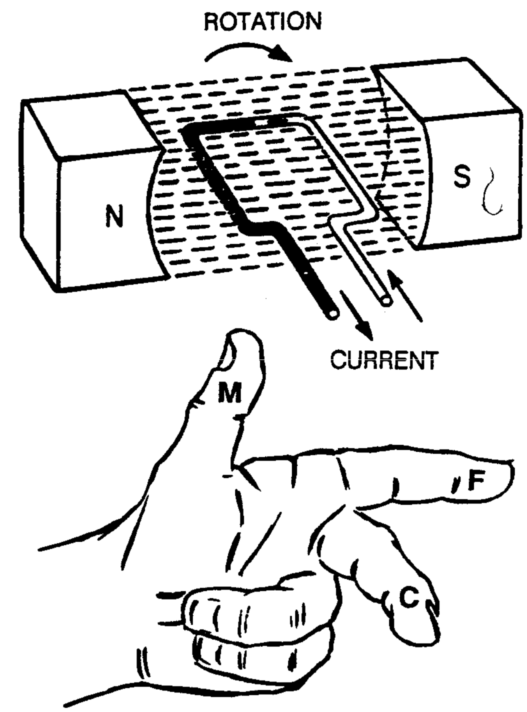


FIGURE 5-8. Basic Alternating Current Generator.

When the loop rotates to the position of view D, the action reverses. The dark half is moving up instead of down, and the light half is moving down instead of up. By applying the left-hand rule once again, the total induced EMF and its resulting current have reversed direction. The voltage builds up to maximum in this new direction, as shown by the sine curve. The loop finally returns to its original position, view E, at which point voltage is again zero. The sine curve represents one complete cycle of voltage generated by the rotating loop. These illustrations show the wire loop moving in a clockwise direction. In actual practice, either the loop or the magnetic field can be moved. Regardless of which is moved, the left-hand rule applies.

If the loop is rotated through 360 degrees at a steady rate and if the strength of the magnetic field is uniform, the voltage produced is a sine wave of voltage (Figure 5-8). Continuous rotation of the loop will produce a series of sine-wave voltage cycles or, in other words, AC voltage.

The cycle consists of two complete alternations in a period of time. The hertz (Hz) indicates one cycle per second. If one cycle per second is 1 hertz, then 100 cycles per second equal 100 hertz, and so on. This text uses the term "cycle" when no specific time element is involved and the term "hertz" when the time element is measured in seconds.



AN EASY WAY TO REMEMBER WHICH FINGER POINTS TO WHAT QUANTITY IS TO USE THE MEMORY AID: MY FINE CLOTHES.
MY = M, DIRECTION OF MOVEMENT
FINE = F, DIRECTION OF FLUX N → S
CLOTHES = C, DIRECTION OF CURRENT FLOW

FIGURE 5-9. Left-Hand Rule for Generators.

FREQUENCY

If the loop makes one complete revolution each second, the generator produces one complete cycle of AC during each second (1 Hz). Increasing the number of revolutions to two per second produces two cycles of AC per second (2 Hz). The number of complete cycles of AC or voltage completed each second is the frequency. Frequency is always measured and expressed in hertz.

PERIOD

An individual cycle of any sine wave represents a definite amount of time. Figure 5-10 shows two cycles of a sine wave that have a frequency of 2 hertz. Since two cycles occur each second, one cycle must require one-half second of time. The time required to complete one cycle of a waveform is the period of the wave. In the above example, the period is one-half second, The relationship between time (t) and frequency (f) is indicated by the following formulas:

$$t = \frac{1}{f} \quad \text{and} \quad f = \frac{1}{t}$$

Where: t = period in seconds
f = frequency in hertz

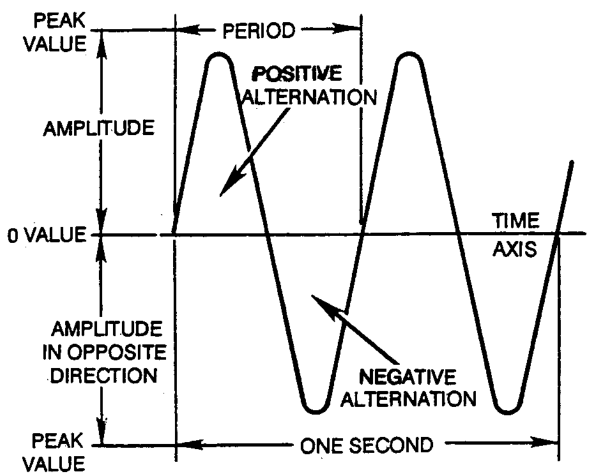


FIGURE 5-10. Period of a Sine Wave.

Each cycle of the sine wave in Figure 5-10 consists of two identically shaped variations in voltage. The variations that occur during the time considered the positive alternation (above the horizontal line) indicate current movement in one direction. The direction of current movement is determined by the generated terminal voltage polarities. The variations that occur during the time considered the negative alternation (below the horizontal line) indicate current movement in the opposite direction because the generated voltage terminal polarities have reversed.

The distance from zero to the maximum value of each alternation is the amplitude. The amplitude of the positive alternation and the amplitude of the negative alternation are the same.

WAVELENGTH

The time it takes for a sine wave to complete one cycle is defined as the period of the waveform. The distance traveled by the sine wave during this period is the wavelength. Wavelength, indicated by the Greek symbol lambda, is the distance along the wave from one point to the same point on the next cycle. Figure 5-11 shows this relationship. The point where waveform measurement of wavelength begins is not important as long as the distance is measured to the same point on the next cycle (Figure 5-12).

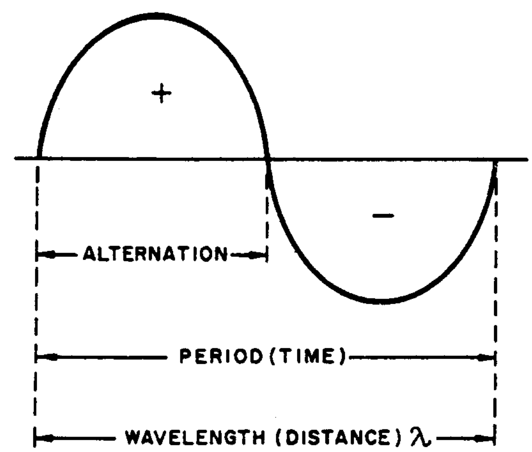


FIGURE 5-11. Wavelength.

The sine wave is usually expressed on a scale in degrees, Rather than express the time involved in minute portions of a second, it is more effective to express the single recurring sine wave by how many degrees it takes to complete a wavelength. Remember how the sine wave was developed. The conductor had to rotate 180 degrees to create the positive alternation and 180 degrees more to create the negative alternation (Figure 5-9). This produced 360 degrees or one complete revolution for a definite period of time. The amount of times this sine wave is repeated every second corresponds to the frequency (cycles per second) and to the speed of the moving conductor (revolutions per minute). This is the beginning of understanding the relationship between frequency, cycles, and the speed of the prime mover.

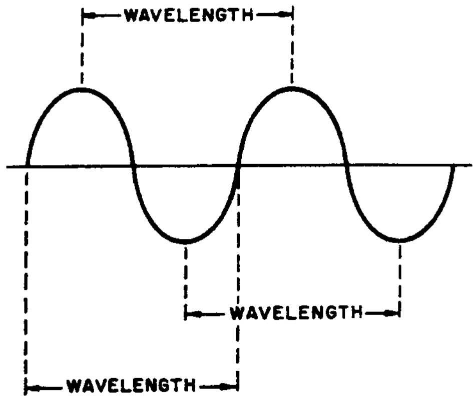


FIGURE 5-12. Wavelength Measurement.

ALTERNATING CURRENT VALUES

AC and voltage are often expressed in terms of maximum or peak values, peak-to-peak values, effective values, average values, or instantaneous values. Each of these values describes a different amount of the current or voltage.

Peak and Peak-to-Peak Values

Figure 5-13 shows the positive alternation of a sine wave (a half-cycle of AC) and a DC waveform that occur simultaneously. The DC starts and stops at the same moment as the positive alternation, and both waveforms rise to the same maximum value. However, the DC values are greater than the corresponding AC values at all points except the point at which the positive alternation passes through its maximum value. At this point, the DC and the AC values are equal. This point on the sine wave is referred to as the maximum or peak value.

During each complete cycle of AC, there are always two maximum or peak values: one for the positive half-cycle and the other for the negative half-cycle. The difference between the peak positive value and the peak negative value is the peak-to-peak value of the sine wave. This value is twice the maximum or peak value of the sine wave and is sometimes used to measure AC voltages. Figure 5-14 shows the difference between peak and peak-to-peak values. Usually, alternating voltage and current are expressed in effective values rather than in peak-to-peak values.

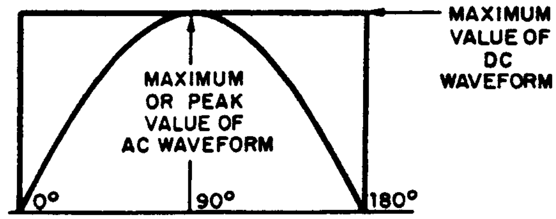


FIGURE 5-13. Maximum or Peak Value.

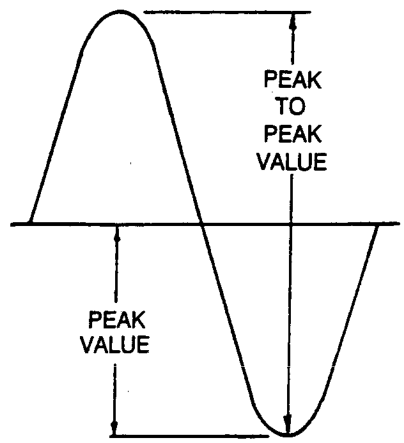


FIGURE 5-14. Peak and Peak-to-Peak Values.

Effective Value

The voltage and current values commonly displayed on multimeters and discussed by technicians is called the effective value. Although AC changes in value constantly, a value closely resembling a like value of DC can be expressed. The effective value of alternating current or voltage has the same effect as a like value of DC. To convert the effective value to a peak value, multiply the effective value by 1.414.

Example:

(450-volt generator effective value) x 1.414 = peak value

(450 volts) x 1.414 = 636.3 volts peak

Conversely, to change the peak value into the effective value, multiply the peak value by .707.

Example:

(636 volt peak value) x .707 = effective value

(636 volts) x .707 = 450 volts effective value

The effective value of alternating current or voltage is also referred to as root mean square or RMS. The RMS value is derived from the power formula. The RMS value turns out to be 70.7 percent of the peak value.

Figure 5-15 shows various values used to indicate sine wave amplitude.

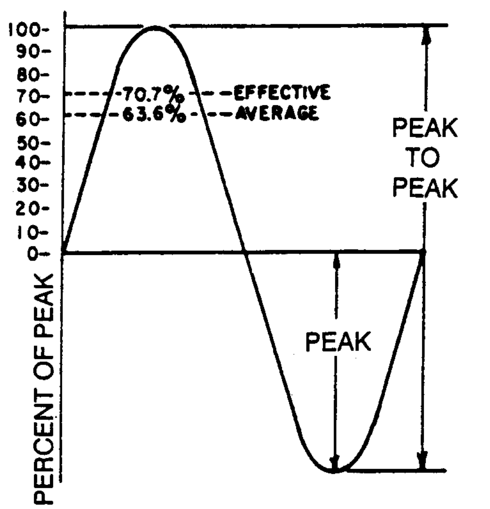


FIGURE 5-15. Various Values Used To Indicate Sine Wave Amplitude.

Instantaneous Value

The instantaneous value of an alternating voltage or current is the value of voltage or current at one particular instant in time. The value may be zero if the particular instant is the time in the cycle at which the polarity of the voltage is changing. It may also be the same as the peak value, if the selected instant is the time in the cycle at which the voltage or current stops increasing and starts decreasing. There are actually an infinite number of instantaneous values between zero and peak value.

Average Value

The average value of an alternating current or voltage is the average of all the instantaneous values during one alternation. Since the voltage increases from zero to peak value and decreases back to zero during one alternation, the average value must be some value between those two limits. The average value can be determined by adding together a series of instantaneous values of the alternation (between 0 and 180 degrees) and then dividing the sum by the number of the instantaneous values used. The computation would show that one alternation of a sine wave has an average value equal to 0.636 times the peak value.

Do not confuse the above definition of an average value with that of the average value of a complete cycle. Because the voltage is positive during one alternation and negative during the other alternation, the average value of the voltage values occurring during the complete cycle is zero.

SINE WAVES IN PHASE

When a sine wave of voltage is applied to a resistance, the resulting current is also a sine wave. This follows Ohm's Law which states that current is directly proportional to the applied voltage. In Figure 5-16, the sine wave of voltage and the resulting sine wave of current are superimposed on the same time axis. As the voltage increases in the positive alternation, the current also increases. When two sine waves, such as those in Figure 5-16, are precisely in step with one another, they are in phase. To be in phase, the two sine waves must go through their maximum and minimum points at the same time and in the same direction.

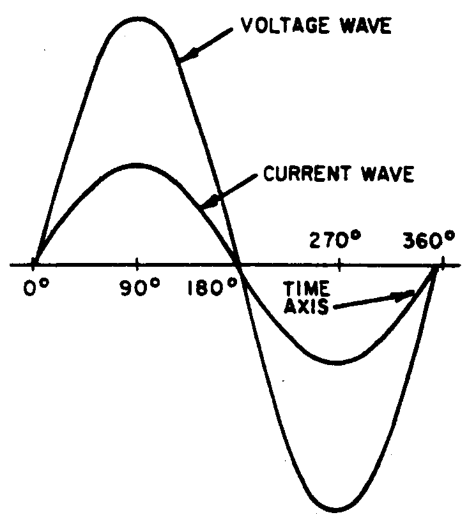


FIGURE 5-16. Voltage and Current Waves in Phase.

This action can only occur in a circuit containing a purely resistive load. A resistive load is any device that consumes all power in the form of heat and/or light. Resistors, light bulbs, and some heating elements are examples of these loads. All the power that arrives at the load is consumed at the load. There is no power left over to be returned to the circuit.

SINE WAVES OUT OF PHASE

Figure 5-17 shows voltage wave El which is considered to start at 0 degrees (time one). As voltage wave El reaches its positive peak, voltage wave E2 starts its rise (time two). Since these voltage waves do not go through their maximum and minimum points at the same instant in time, a phase difference exists between the two waves. The two waves are out of phase. For the two waves in Figure 5-17, the phase difference is 90 degrees.

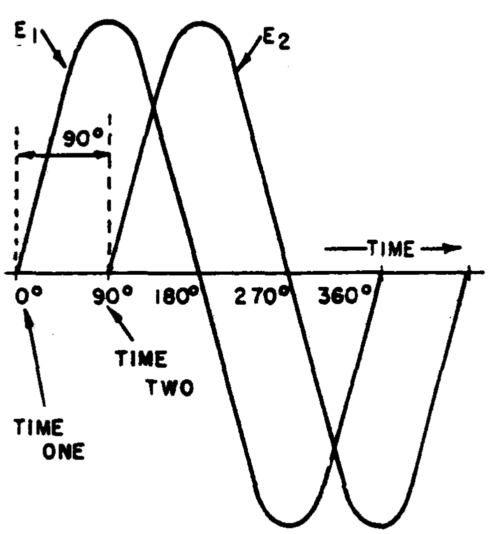


FIGURE 5-17. Voltage Waves 90 Degrees Out of Phase.

The terms "lead" and "lag" further describe the phase relationship between two sine waves. The amount by which one sine wave leads or lags another sine wave is measured in degrees. In Figure 5-17, wave E2 starts 90 degrees later in time than does wave El. Wave El leads wave E2 by 90 degrees, and wave E2 lags wave El by 90 degrees.

One sine wave can lead or lag another sine wave by any number of degrees, except 0 or 360. When the latter condition exists, the two waves are said to be in phase. Thus, two sine waves that differ in phase by 45 degrees are actually out of phase with each other; whereas two sine waves that differ in phase by 360 degrees are considered to be in phase with each other.

Figure 5-18 shows a common phase relationship. The two waves illustrated differ in phase by 180 degrees. Although the waves pass through their maximum and minimum values at the same time, their instantaneous voltages are always of opposite polarity.

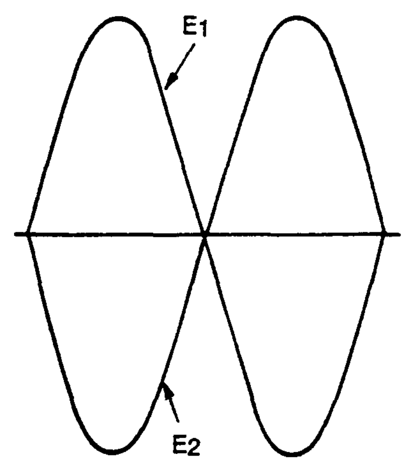


FIGURE 5-18. Voltage Waves 180 Degrees Out of Phase.

To determine the phase difference between two sine waves, locate the points where the two waves cross the time axis traveling in the same direction. The number of degrees between the crossing points is the phase difference. The wave that crosses the axis at the later time (to the right on the time axis) is said to lag the other wave.

OHM'S LAW IN AC CIRCUITS

Few shipboard circuits contain resistance only. For those circuits that contain purely resistive loads, the same rules apply to these circuits as apply to DC circuits. Ohm's Law for purely resistive circuits can be stated as follows

$$I_{eff} = \frac{E_{eff}}{R} \text{ or } I = \frac{E}{R}$$

Unless otherwise stated, all AC voltage and current values are given as effective values. Do not mix AC values. When solving for effective values, all values used in the formulas must be effective values. Similarly, when solving for average values, all values must be average values.

There are many other factors affecting the mathematical values of AC electrical systems. Even with these other outside variables, the marine engineer can use Ohm's Law to understand the relationship between voltage, current, and resistance.